

Study of higher mass exotic resonances in pp collisions at $\sqrt{s} = 13.6$ TeV in ALICE

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OUTLINE

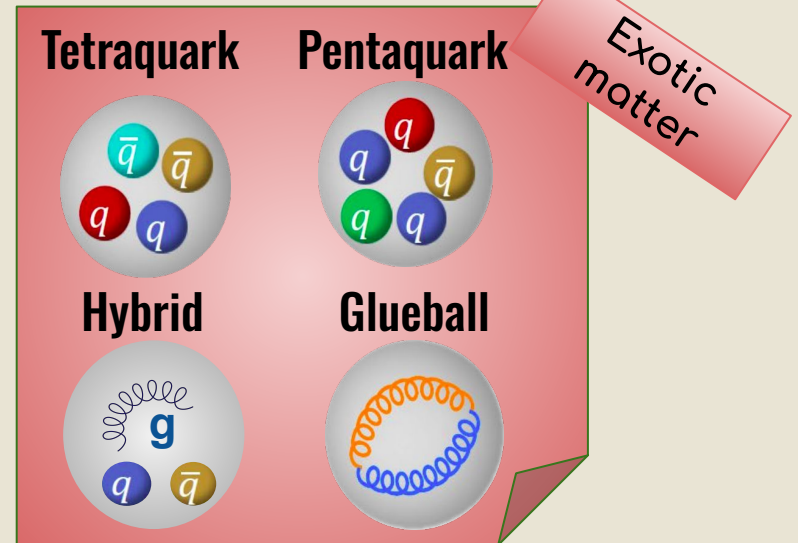
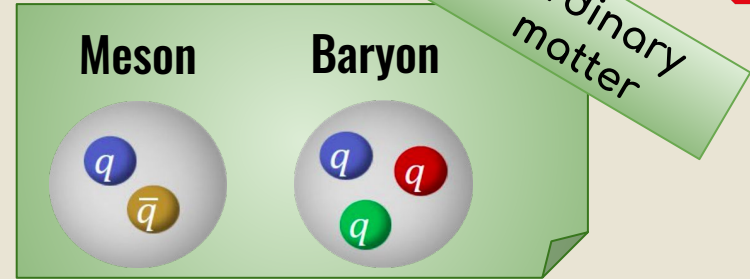
- Theory and motivation
- Dataset and analysis details
- Results
- Summary and outlook



Introduction to exotic QCD states



- **Standard model:** Describes ordinary hadrons as mesons and baryons
- **QCD predictions:** Existence of exotic states beyond the conventional hadrons [1]
- **Exotic states:** Tetraquark, pentaquark, molecular, hybrid, and glueballs [2,3]
- **Glueball:** A bound state made entirely of gluons. Their self interaction is possible due to their color charge in QCD.
- **Exotic hadrons study:** Test and validate QCD predictions



[1] M. Gell-Mann, Phys. Lett. 8, 214

[2] R. Aaij et al., Sci. Bull. 65, 1983

[3] R. Aaij et al., Phys. Rev. Lett. 115, 072001

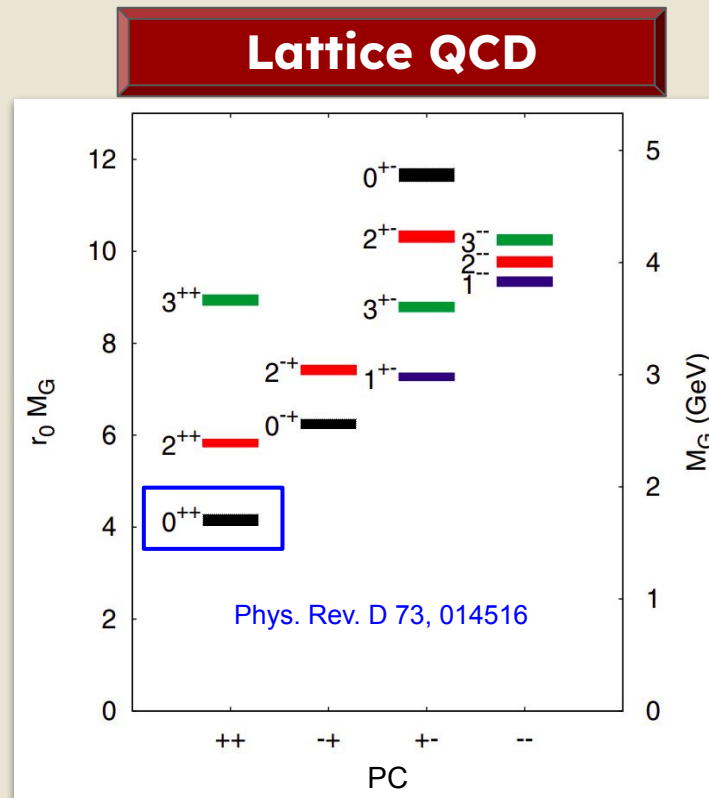
Lattice QCD prediction



- **Lattice QCD prediction:** Existence of glueball and its excited states in the mass range 1 - 5 GeV/c²
- **Lightest scalar glueball [1]:**
 - ✓ **Quantum numbers:** $J^{PC} = 0^{++}$
 - ✓ **Mass range:** 1.5 - 1.8 GeV/c²
 - ✓ **Decay channel:** KK, $\pi\pi$, $\eta\eta$
- **Lightest scalar glueball candidate $f_0(1710)$ [2]:**
 - ✓ **Decay pattern:** Larger coupling to KK than $\pi\pi$

[1] W. Ochs, J. Phys. G: Nucl. Part. Phys. 40, 043001

[2] H.Y. Cheng et al., Phys. Rev. D 92, 094006.



Lightest scalar glueball searches at HERA experiment

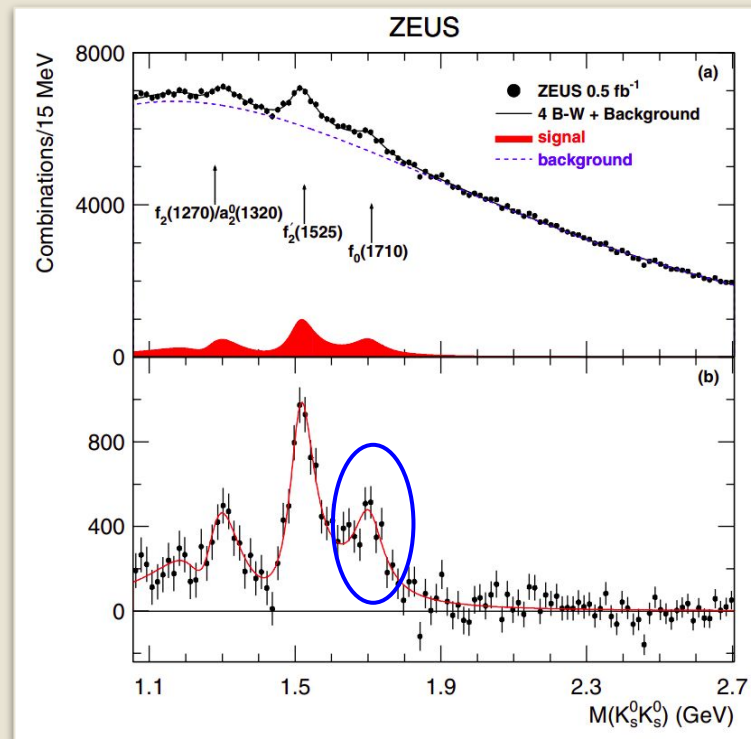


- HERA experiment (ep collisions):
 - ✓ Data collected using ZEUS detector (1996-2007) at $\sqrt{s} = 318$ GeV
 - ✓ Invariant mass reconstruction in $K_s^0 K_s^0$ decay channel
 - ✓ Resonances observed: $f_2(1270)/a_2(1320)$, $f_2(1525)$, and $f_0(1710)$
 - ✓ Lightest scalar glueball candidate $f_0(1710)$ observed with 5σ statistical significance

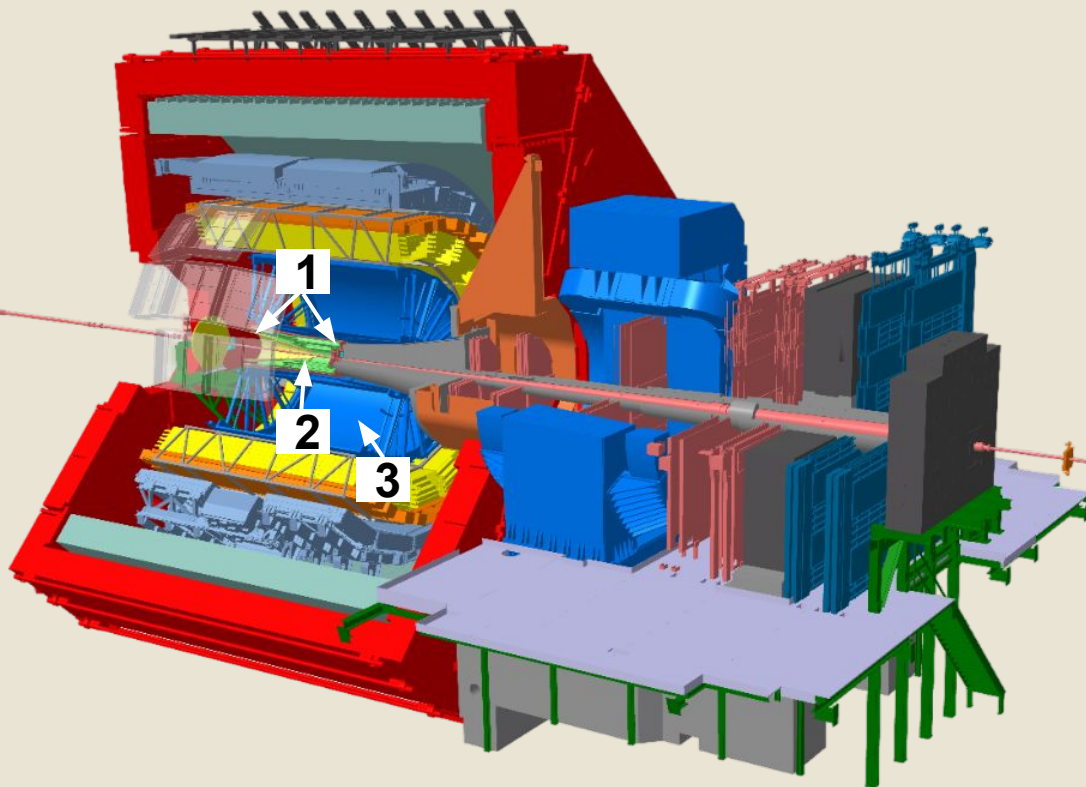
Do we also observe the glueball candidate $f_0(1710)$ using $K_s^0 K_s^0$ decay channel in pp collisions with ALICE?

S. Chekanov et al., Phys. Rev. Lett. 101, 112003

$K_s^0 K_s^0$ invariant mass spectrum



ALICE Run 3 detector



1. Fast Interaction Trigger

- ✓ Centrality/multiplicity estimator

2. Inner Tracking System

- ✓ Tracking and vertexing

3. Time Projection Chamber

- ✓ Tracking
- ✓ Momentum measurement
- ✓ Particle Identification (PID) via specific energy loss (dE/dx)

ALICE Run 3 data, with large statistics and the highest center-of-mass energy, provides a unique opportunity for the study of exotic particles

Dataset, event and track selection



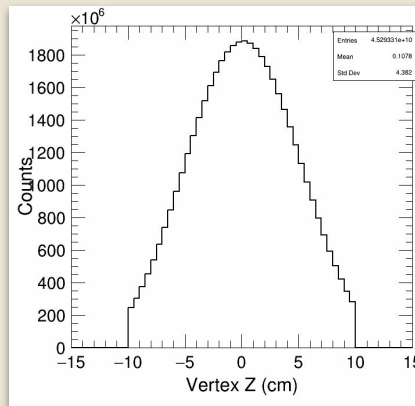
Dataset:

- ✓ Collision system: pp
- ✓ Center-of-mass energy = 13.6 TeV
- ✓ Period: LHC22o_pass7
- ✓ Events analyzed (accepted): ~47.5 billion

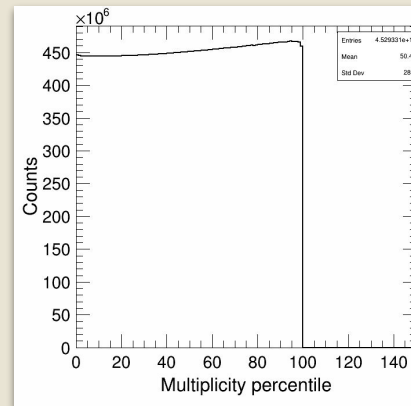
Event selection:

- ✓ Minimum bias trigger
- ✓ $|V_Z| < 10$ cm

$|v_Z|$ distribution after applying $|v_Z| < 10$ cm



FT0M multiplicity percentile distribution



Track selection and PID:

- ✓ $|\eta| < 0.8$
- ✓ No. of TPC crossed rows > 70
- ✓ No. of crossed rows over findable clusters > 0.8
- ✓ $|DCA \text{ negative \& positive track to PV}| > 0.05$ cm
- ✓ $|n\sigma_{\text{TPC}}| < 3$

Analysis details



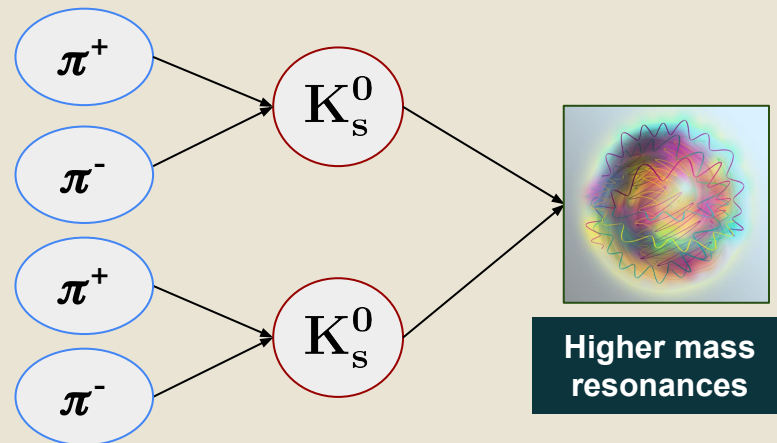
Invariant mass reconstruction:

$$M_{\text{inv}} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2}$$

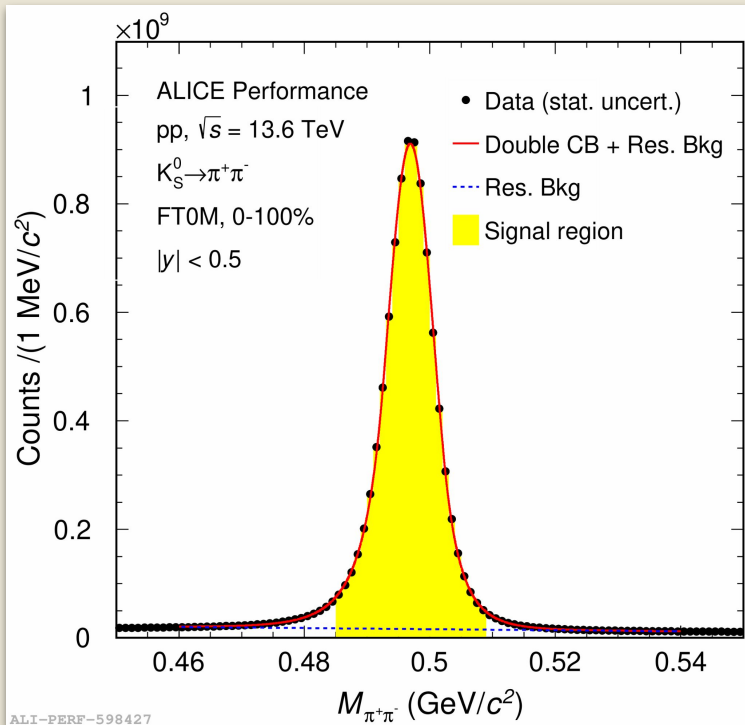
1. Reconstruction of K_s^0 from $\pi^+\pi^-$
2. Reconstruction of higher mass resonances from $K_s^0 K_s^0$

Higher mass resonances:

- ✓ Integrated p_T bin: 0-30 GeV/c
- ✓ Minimum bias: 0-100% (multiplicity estimator; FT0M)
- ✓ Decay channel: $K_s^0 K_s^0$
- ✓ Combinatorial background: Rotational background (RB)
- ✓ RB: One daughter is rotated 3 times randomly within the angle by $\pi \pm \pi/10$



K_s^0 selection and reconstruction from $\pi^+\pi^-$ pair



Candidate selection

- ✓ $p_T > 0.2 \text{ GeV}/c$, $|y| < 0.5$

Topological selection

- ✓ V0 lifetime ($c\tau$) $< 20 \text{ cm}$
- ✓ Decay radius $> 0.5 \text{ cm}$
- ✓ $\cos\text{PA} > 0.97$
- ✓ DCA V0 daughters $< 1 \text{ cm}$
- ✓ Competing V0 rejection: $|M_{\text{pp}} - M_{\Lambda}| < 5 \text{ MeV}$

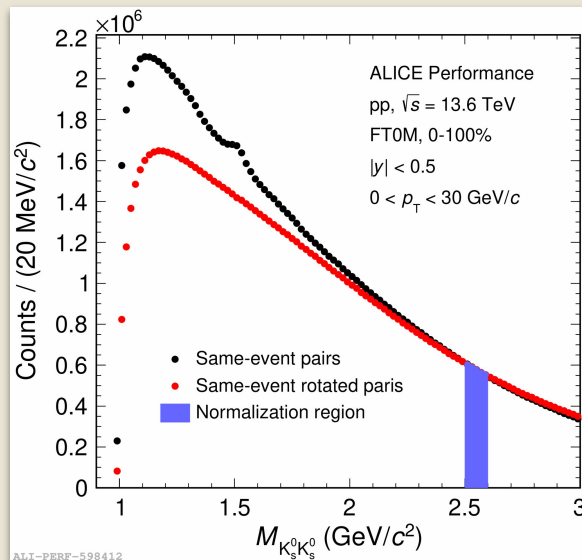
$\pi^+\pi^-$ pair invariant mass

- ✓ The distribution is fitted with Double Crystal ball + pol 2
- ✓ PDG mass of K_s^0 : $497.611 \pm 0.013 \text{ MeV}/c^2$
- ✓ Mass peak obtained from fit: $496.92 \text{ MeV}/c^2$
- ✓ For the $K_s^0 K_s^0$ invariant mass reconstruction:
 K_s^0 selection: $\pm 4\sigma$ from PDG mass (yellow band)

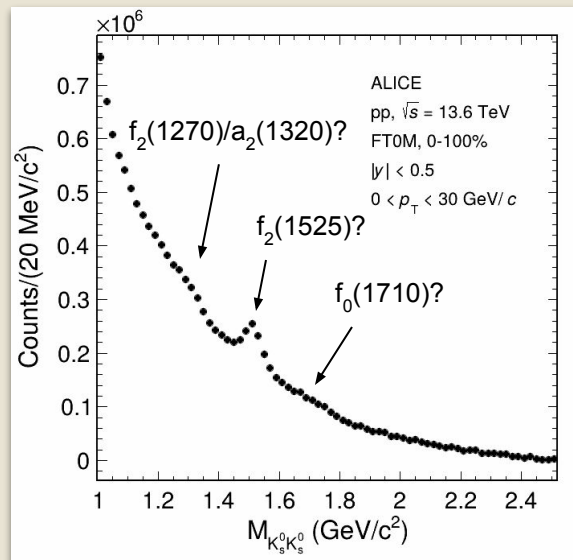
Resonance reconstruction from $K_s^0 K_s^0$ pair



$K_s^0 K_s^0$ invariant mass distribution



Background subtracted $K_s^0 K_s^0$ invariant mass



$K_s^0 K_s^0$ invariant mass distribution before and after normalized rotational background subtraction.

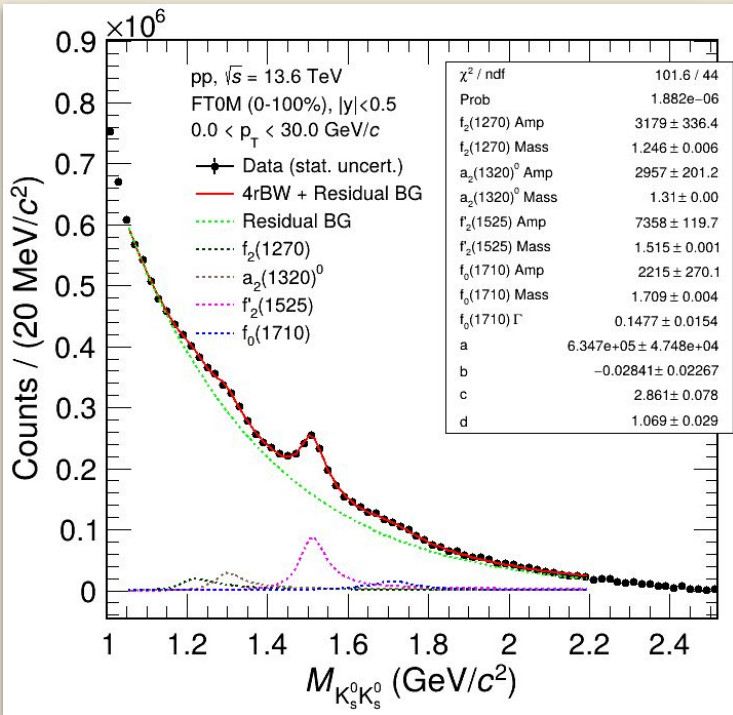
- ✓ Three peaks are seen around invariant masses 1.3, 1.5, and 1.7 GeV/c².
- ✓ Expected resonances in this mass range according to HERA experiment [1]:
 - ◆ $f_2(1270)/a_2(1320)$
 - ◆ $f_2(1525)$
 - ◆ $f_0(1710)$

[1] [S. Chekanov et al., Phys. Rev. Lett. 101, 112003](#)

Signal extraction



$K_s^0 K_s^0$ invariant mass distribution fit



- $K_s^0 K_s^0$ invariant mass distribution after rotational background subtraction
- **Signal fit function:** Relativistic Breit-Wigner function with mass dependent width [1]:

where,

$$rBW(M) = \frac{A_0 M \Gamma(M) M_0}{(M_0^2 - M^2)^2 + M_0^2 \Gamma^2(M)}$$

- M is $K_s^0 K_s^0$ invariant mass
- M_0 and Γ is mass peak and width
- $M_{K_s^0}$ is the mass of K_s^0
- Spin angular momentum (J):
 - ✓ J = 2 for $f_2(1270)$, $a_2(1320)$, and $f_2(1525)$
 - ✓ J = 0 for $f_0(1710)$

$$\Gamma(M) = \left[\frac{M^2 - 4M_{K_s^0}^2}{M_0^2 - 4M_{K_s^0}^2} \right]^{(2J+1)/2} \times \frac{\Gamma_0 M_0}{M}$$

- **Background fit function:** Modified Boltzmann function

$$f_{\text{bkg}}(M) = a(M - 2M_{K_s^0})^b e^{-c(M - 2M_{K_s^0})^d}$$

Fit function: 4 rBW (signal) + Modified Boltzmann (background)

Resonances: $f_2(1270)$, $a_2(1320)$, $f_2(1525)$, and $f_0(1710)$.

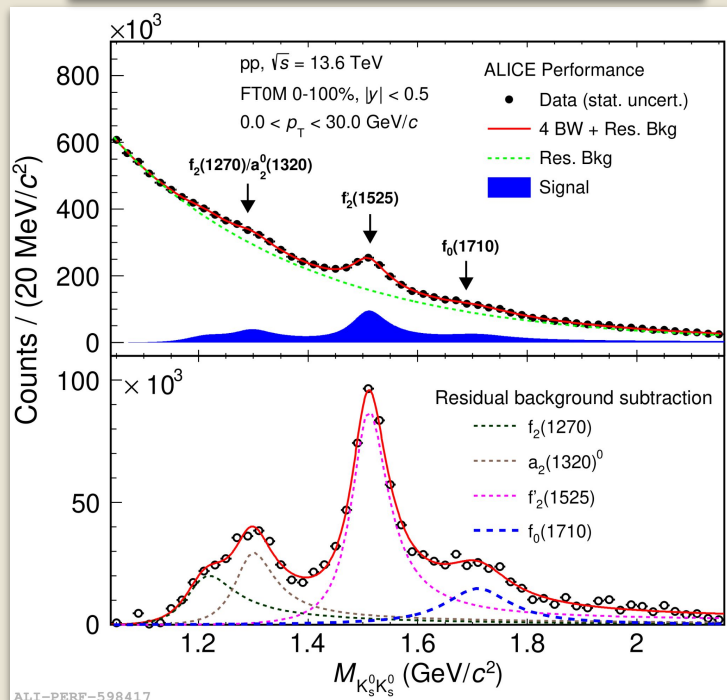
Fixed parameters: Width (Γ_0) of spin-2 resonances are fixed to PDG value.

[1] Phys. Lett. B 846 (2023) 137644

Signal extraction



$K_S^0 K_S^0$ invariant mass distribution fit



★ Significance $\left(\frac{S}{\sqrt{S+B}}\right)$ of $f_0(1710)$ signal in $\pm 2\sigma$ is 22.7

- ✓ **Fit function:**
 Independent sum of 4 rBW (mass-dependent width) (signal)
 + modified Boltzmann function (background)
- ✓ **Top panel:** Invariant mass distribution after combinatorial background subtraction.
- ✓ **Bottom panel:** Invariant mass distribution after residual background subtraction. Fit with only signal fit function (4 rBW) with initial parameter guess from top panel fit.

$f_0(1710)$ resonance	This analysis	PDG 2024
Mass (MeV/c ²)	1708.7 ± 4.3	1733 ± 8
Width (MeV/c ²)	147.7 ± 15.6	150 ± 12

[1] S. Navas *et al.* (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

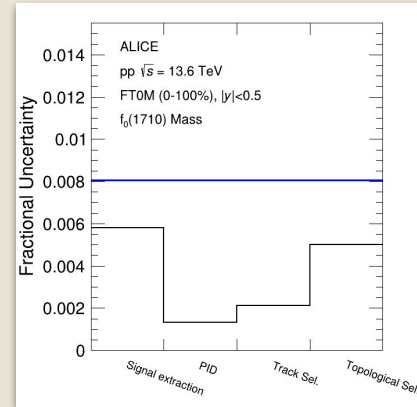
Systematic study



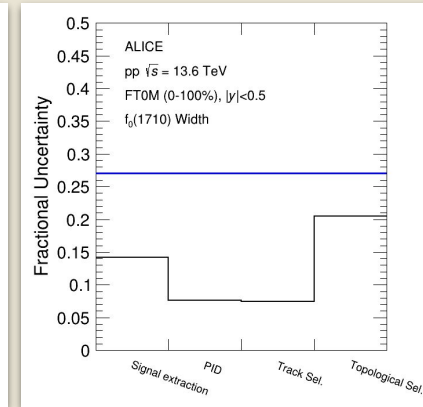
Systematic sources for systematic study:

- ◆ **Signal extraction**
- ◆ **PID selection:** Default ($\pm 3\sigma$), Variation ($\pm 4\sigma, \pm 5\sigma$)
- ◆ **Track selection:**
 - ✓ DCA track to PV: Default (>0.05 cm), Variation (>0.04 cm, 0.06 cm)
 - ✓ TPC crossed rows: Default (>70), Variation ($100, 120$)
 - ✓ TPC crossed rows over findable clusters: Default (>0.8), Variation ($>0.9, 1.0$)
- ◆ **Topological selection:**
 - ✓ Cosine PA: Default (>0.97), Variation ($>0.95, 0.99$)
 - ✓ Transverse decay radius: Default (> 0.5 cm), Variation ($>0.4, 0.6$ cm)
 - ✓ DCA b/w v0 daughters: Default (> 0.5 cm), Variation ($>0.3, 1.0$ cm)
 - ✓ Proper lifetime: Default (< 20 cm), Variation ($< 15, 25$ cm)
 - ✓ Competing v0 rejection: Default (< 5 MeV/c²), Variation ($< 4, 6$ MeV/c²)
 - ✓ $N\sigma$ selection on K^0_s mass: Default (3σ), Variation ($2,4 \sigma$)

Total Systematic uncertainty in mass

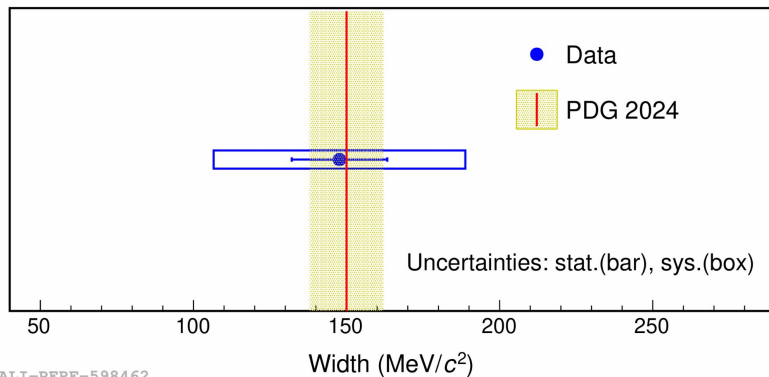
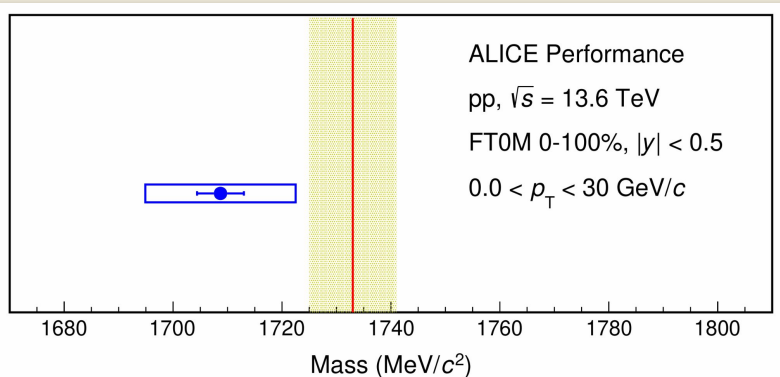


Total Systematic uncertainty in width



- ✓ Total systematic uncertainty is quadrature sum of all four sources.
- ✓ Total systematic uncertainty in mass is 0.81 %
- ✓ Total systematic uncertainty in width is 27.8 %.

$f_0(1710)$ mass and width comparison with PDG



ALI-PERF-598462

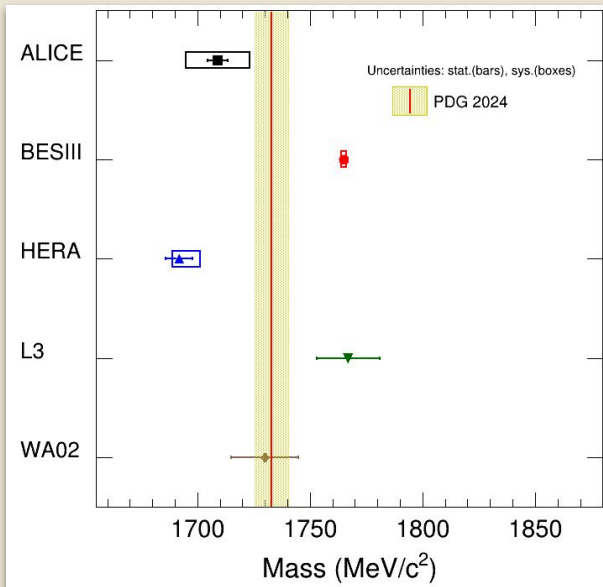
$f_0(1710)$ resonance	This analysis	PDG 2024
Mass (MeV/c ²)	1708.7 ± 4.3 (stat.) ± 13.8 (sys.)	1733 ± 8
Width (MeV/c ²)	147.7 ± 15.6 (stat.) ± 41.1 (sys.)	150 ± 12

- ◆ The mass and width of $f_0(1710)$ resonance is comparable with the PDG within uncertainties.
- ◆ The significance of signal is 22.7.

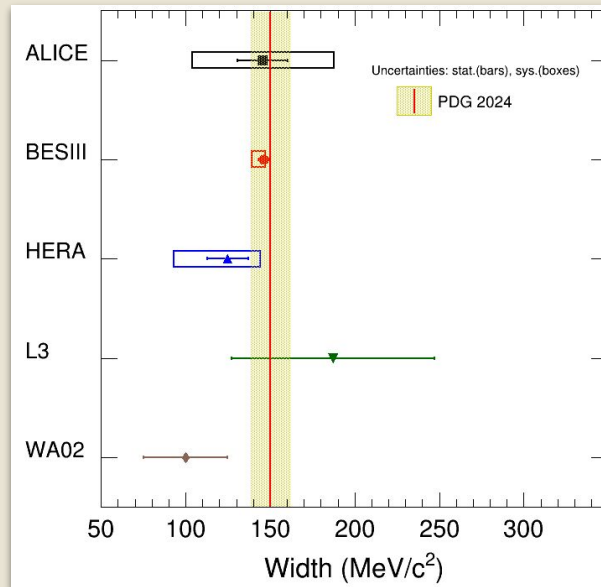
$f_0(1710)$ mass and width in different experiments



$f_0(1710)$ mass



$f_0(1710)$ width



✓ The mass of $f_0(1710)$ resonance in pp 13.6 TeV, is comparable to the PDG, HERA experiment, and WA02 within $\sim 1\sigma$.

✓ The width is comparable with all experiments within the uncertainties.

- **ALICE:** $K_s^0 K_s^0$ decay channel in pp collisions at $\sqrt{s} = 13.6$ TeV
- **BES III:** $\gamma K_s^0 K_s^0$ system in radiative J/Ψ decays in e^+e^- collisions at $\sqrt{s} = 2 - 4.6$ GeV
- **HERA:** $K_s^0 K_s^0$ decay channel in ep collisions at $\sqrt{s} = 318$ GeV
- **L3:** $K_s^0 K_s^0$ decay channel in e^+e^- collisions at $\sqrt{s} = 183 - 202$ GeV
- **WA02:** K^+K^- and $K_s^0 K_s^0$ decay channel in pp collisions at $\sqrt{s} = 450$ GeV



Summary

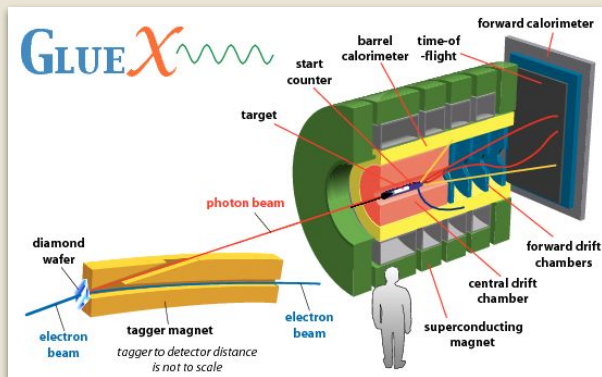
- ❖ $K_s^0 K_s^0$ invariant mass distribution in pp collisions at $\sqrt{s} = 13.6$ TeV, using the latest Run 3 data is presented.
- ❖ Four resonance structures were observed in the 1-3 GeV/c² mass range for the integrated p_T range of 0–30 GeV/c.
- ❖ Fit function with 4 rBW (mass dependent width) (signal) and modified Boltzmann (background) function is used.
- ❖ Mass and width of the glueball candidate $f_0(1710)$ is obtained and systematic studies were performed.
- ❖ Mass and width of $f_0(1710)$ are compared with the PDG values and other experiments.

Outlook

- ❖ Differential p_T studies to obtain the resonance spectra
- ❖ Resonance injected MC studies to obtain corrected spectra
- ❖ Partial wave analysis to investigate the spin of resonances

★ More details on the analysis can be found in the analysis note <https://alice-notes.web.cern.ch/node/1598>.

Future experiments focused on exotic resonance searches



GlueX Experiment (J-Lab)

Will be helpful in discovering glueballs by studying the interactions of high-intensity photon beams with protons.

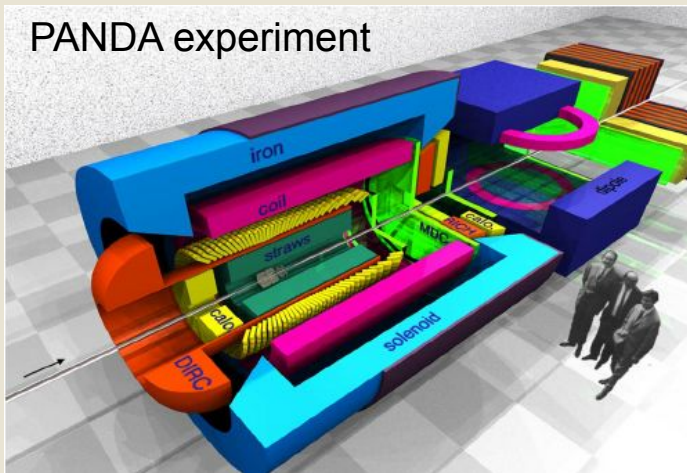
PANDA Experiment (FAIR)

Focuses on discovering glueballs and other exotic hadrons using antiproton-proton collisions.

LHCb searches

Focuses on discovering exotic hadrons using pp and heavy ion collision in LHC.

PANDA experiment



[R. Aaij et al., Sci. Bull. 65, 1983](#)

[Al Ghoul, H. et al. Phys. Rev. C 95, 042201](#)

[W. Kuhn et al. 2007 15th IEEE-NPSS Conference, pp. 1-2](#)



THANK YOU!